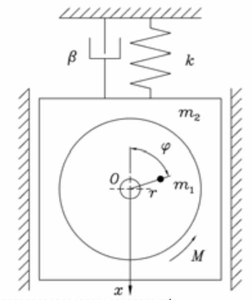
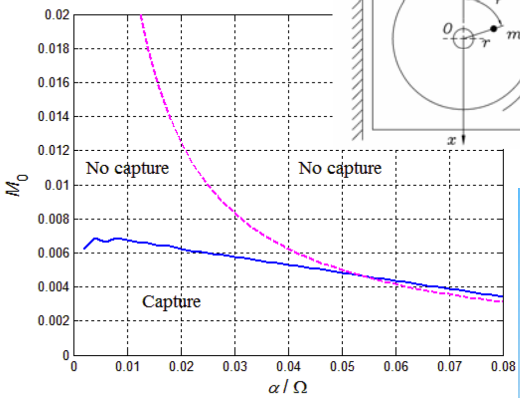
Principal servocontroller failure modes and effects on active flutter suppression

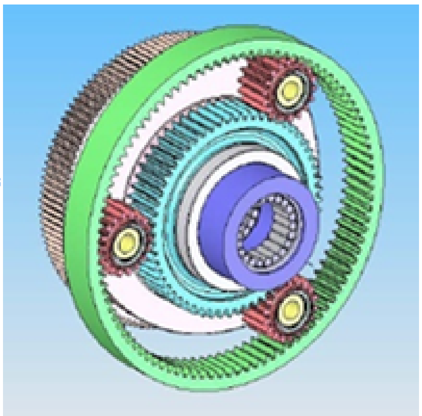
ISSN 1590-8844
Vol. 11 No 02
2010

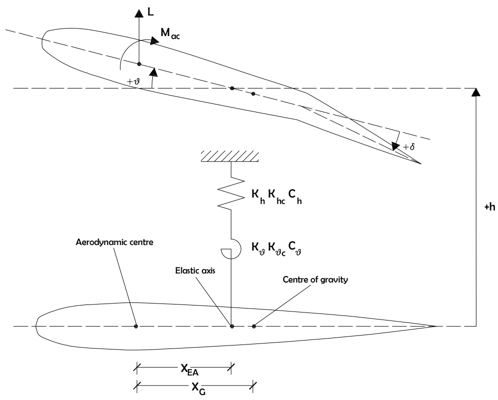
International Journal of Mechanics and Control

Editor: Andrea Manuello Bertetto









LIBRERIA EDITRICE UNIVERSITARIA
LEVROTTO & BELLA
TORINO

Official Torino Italy Court Registration
n.5390, 5th May 2000

Deposito presso il Tribunale di Torino
numero 5390 del 5 maggio 2000
Direttore responsabile:
Andrea Manuello Bertetto

International Journal of Mechanics and Control

The Journal is addressed to scientists and engineers who work in the fields of mechanics (mechanics, machines, systems, control, structures). It is edited in Turin (Northern Italy) by Levrotto&Bella Co., with an international board of editors. It will have not advertising.
Turin has a great and long tradition in mechanics and automation of mechanical systems. The journal would will to satisfy the needs of young research workers of having their work published on a qualified paper in a short time, and of the public need to read the results of researches as fast as possible.
Interested parties will be University Departments, Private or Public Research Centres, Innovative Industries.

Aims and scope
The *International Journal of Mechanics and Control* publishes as rapidly as possible manuscripts of high standards. It aims at providing a fast means of exchange of ideas among workers in Mechanics, at offering an effective method of bringing new results quickly to the public and at establishing an informal vehicle for the discussion of ideas that may still in the formative stages.

Language: English
International Journal of Mechanics and Control will publish both scientific and applied contributions. The scope of the journal includes theoretical and computational methods, their applications and experimental procedures used to validate the theoretical foundations. The research reported in the journal will address the issues of new formulations, solution, algorithms, computational efficiency, analytical and computational kinematics synthesis, system dynamics, structures, flexibility effects, control, optimisation, real-time simulation, reliability and durability. Fields such as vehicle dynamics, aerospace technology, robotics and mechatronics, machine dynamics, crashworthiness, biomechanics, computer graphics, or system identification are also covered by the journal.

Please address contributions to

Prof. Guido Belforte
Prof. Andrea Manuello Bertetto
PhD Eng. Elvio Bonisoli

Dept. of Mechanics
Technical University - Politecnico di Torino
C.so Duca degli Abruzzi, 24.
10129 - Torino - Italy - E.C.

www.jomac.it
e_mail: jomac@polito.it

Subscription information

Subscription order must be sent to
the publisher:

Libreria Editrice Universitaria
Levrotto&Bella
2/E via Pigafetta – 10129 Torino – Italy

www.levrotto-bella.net
e_mail: info@levrotto-bella.net
tel. +39.011.5097367
+39.011.5083690
fax +39.011.504025

ISSN 1590-8844
International Journal of Mechanics and Control, Vol. 11, No. 02, 2010

PRINCIPAL SERVOCONTROLLER FAILURE MODES AND EFFECTS ON ACTIVE FLUTTER SUPPRESSION

Lorenzo Borello* Giuseppe Villero* Matteo Dalla Vedova*

* Department of Aerospace Engineering, Politecnico di Torino, Turin, Italy

ABSTRACT

Conventional active flutter and vibration control technology relies on the use of aerodynamic control surfaces operated by servo-hydraulic actuators, which can be affected by some specific types of failure. In order to assure a sufficiently high safety degree, it is necessary to verify the dynamic behaviour of the whole system when a defined failure occurs. The purpose of this paper is to analyze the aeroservoelastic behaviour of a typical wing with active flutter suppression performed by a hydraulic servomechanism equipped with a defined proper control law (relating the required surface deflection angle to speeds and acceleration of the main aerofoil surface) and affected by the principal modes of servocontroller failures. Active control and its failure modes have been implemented within the model of a representative actuation system acting on a wing structure embedded in a defined aerodynamic field.

Keywords: Failure, flutter, flight controls, active suppression.

1 INTRODUCTION

Aeroelasticity is the mutual interaction between deformations of the elastic structure and aerodynamic forces induced by the structure deformations. Combined, these effects may cause an aircraft structure to become unstable above a defined value of flight speed. If the interaction between deformations and aerodynamic forces involves also the inertia, the phenomenon, called flutter, is an oscillatory instability that occurs when the structural damping transitions from positive to negative due to the presence of aerodynamic forces. During this transition, two modes of vibration coalesce to the same frequency and achieve an aeroelastic resonance. Bending and torsion are the two most common vibration modes of a wing which coalesce to flutter. In modern aircrafts the use of automatic flight control systems with powered control surfaces has further complicated the problem.

Contact author: Borello[1], Villero[2], Dalla Vedova[3]

[1] lorenzo.borello@polito
[2] giuseppe.villero@polito
[3] matteo.dallavedova@polito.it
Corso Duca degli Abruzzi 24 – 10129 TORINO

This interaction between structural dynamics, unsteady aerodynamics and the flight control system of the aircraft, known as aeroservoelasticity, has been and continues to be an extremely important consideration in many aircraft designs. To prevent undesirable aeroelastic effects, the stiffness of the wing must be increased, adding weight to the aircraft and decreasing the overall performance: this approach is known as “passive control”. A recent alternative to passive control is the so called “active control” through feedback to control surfaces (conventional technique), or, more recently, through feedback to active materials. These vibration control technologies allow flight vehicles to operate beyond the traditional flutter boundaries, improve ride qualities, and minimize vibration fatigue damage. Many control strategies have been applied to suppress flutter or to control unacceptable wing motion. Conventional active flutter and vibration control technology relies on the use of aerodynamic control surfaces operated by servo-hydraulic actuators. In this conventional configuration the flutter and vibration suppression algorithms are implemented through the servovalve/hydraulic actuator, capable of producing (if necessary in presence of large oscillation amplitude) large forces and large surface displacement, but having some limitations, such as limited actuation speed in saturation conditions and limited frequency range. In contrast, active materials technologies offer high-frequency responses but their typical shortcomings are limited forces and displacements performed.

Generally, these problems have been already studied by several authors, but no work specifically concerns the effects on the aeroelastic system of the most important failure modes affecting the flutter servocontroller, as:

- servovalve feedback spring failure
- hydraulic system pressure drop
- whole active flutter control failure
- piston seizure
- piston internal sealing failure.

The aim of this paper is the analysis of the aeroservoelastic behaviour of a typical wing with active flutter suppression performed, through a defined control law, by a fly-by-wire hydraulic servomechanism affected by the aforesaid modes of servocontroller failures.

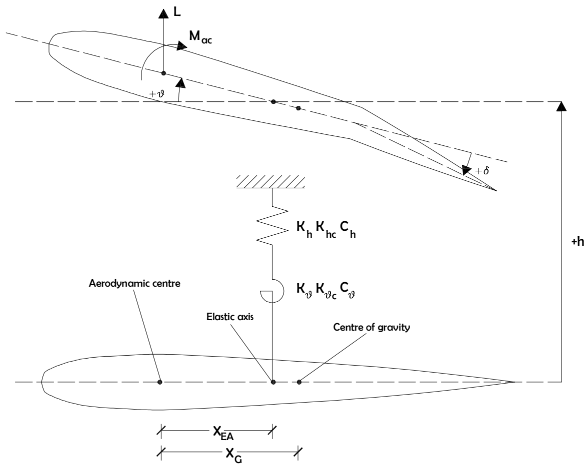


Figure 1 Aeroelastic parameter definition.

2 DESCRIPTION OF AEROSERVOELASTIC MODEL

Figure 1 shows the typical wing section that is used to derive the structural equations of motion. The two degrees of freedom associated with the aerofoil motions are the vertical displacement h and the pitching displacement θ.

The displacements are restrained by a pair of springs attached to the elastic axis with linear spring constants K_θ and K_h and cubic one $K_{\theta c}$ and K_{hc} respectively. The airfoil is equipped with a trailing edge moving surface, whose position δ depends exclusively on the servomechanism position and is not affected by the aerodynamic and inertial loads. The servomechanism position depends, through its dynamic model, on the output of an adequate flutter suppression control law. The aerodynamic model computes lift and pitch moment related to the aerodynamic centre as a function of the dynamic pressure, the initial value of the angle of attack α, the pitching displacement θ, the vertical and pitching rates and the surface deflection angle δ.

The structural dynamic model computes vertical and pitching accelerations related to the elastic axis as a function of aerodynamic loads L and M_{ac}, inertial loads, weight, structural damping and stiffness. The structural damping is considered as a linear function of the speed, while the structural stiffness is modelled as a linear and cubic function of the displacement. The sign of the cubic coefficient takes into account the softening or hardening effects. The actuation system of the aerodynamic surfaces consists of a Power Control and Drive Unit (PDU, equipped with position transducers and tachometers), directly connected to the lever arm of the surfaces. The system control is performed by an Electronic Control Unit (ECU), which closes the position control loop. The PDU contains the hydraulic jack and the control valve.

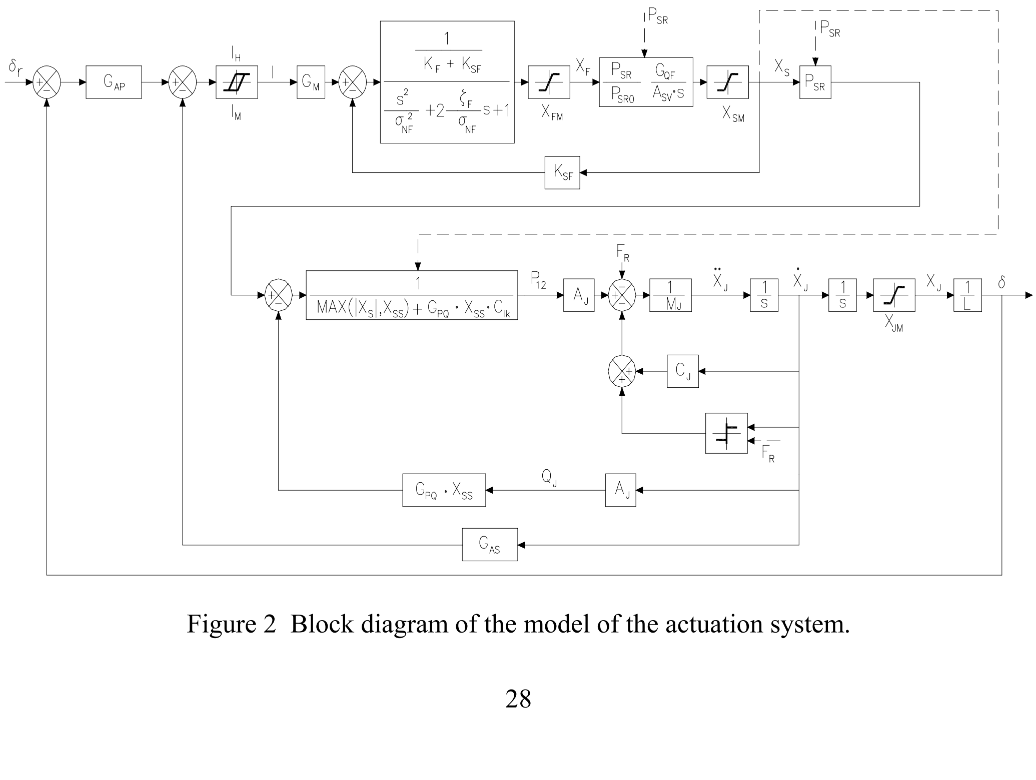


Figure 2 Block diagram of the model of the actuation system.

The model of the actuation system, as reported in figure 2, takes into account the hydraulic and mechanical characteristics of all system components as follows:

- Coulomb friction in the PDU-surface assembly;
- third order electromechanical dynamic model of the servovalve with first and second stage ends of travel;
- fluid-dynamic model of the servovalve taking into account the maximum differential pressure, eventually time varying, performed by the hydraulic system1;
- dynamic and fluid-dynamic of hydraulic jack taking into account, beside the above mentioned Coulomb friction, viscous friction and internal leakage.

The high complexity of the actuation system servomechanism model is requested by the necessity of taking into account the effects of the above mentioned several nonlinearities on the effectiveness of the flutter suppression active control.
Active control has been implemented within the proposed model, in order to investigate active means of flutter suppression via control surface motion. A simple control law is used which relates the required surface deflection angle δ_r to the speed and the acceleration of the main aerofoil surface (heave and pitch degrees of freedom). Hence, δ_r is evaluated according to the following equation:

$$\delta_r = G_{h2}\ddot{h} + G_{h1}\dot{h} + G_{\vartheta 2}\ddot{\vartheta} + G_{\vartheta 1}\dot{\vartheta} \qquad (1)$$

where the G's are the gains of the system.

3 SYSTEM COMPUTATIONAL MODELLING AND RESULTS

The above described models have been used to build a mathematical model of the whole system and a dedicated computer code has been prepared. A structural model having linear and cubic softening spring characteristics around the pitch axis and linear along the vertical displacement is considered. The aerodynamic model is described as linear and the considered flight speed is slightly greater than the critical flutter speed.
Some simulations have been run in different failure conditions, in order to verify the criticality of the actuation system failures on the flutter suppression active control. All the following figures show the behavior of the system in terms of vertical displacement h and pitching angular displacement θ: their trend is typically oscillatory, characterized by a frequency slightly depending on the corresponding amplitude, having an average value of approximately 14,5 Hz. The curves reported in the figures represent the envelopes of the eventually damped oscillations.
Figure 3 shows the behaviour of the system characterized by a fully operational (no failures) active flutter control, in terms of vertical displacement h and pitching angular displacement θ, employing the control law (1) applying a not null value only to the gain $G_{\theta 2}$, because this is a satisfying solution as discussed in [1].
In this case the slow growth of the oscillations amplitude, following the application of a large step perturbation concerning the pitching displacement at time t = 1 s, is suppressed by the active flutter control.
This case must be considered as reference condition for the following simulations.

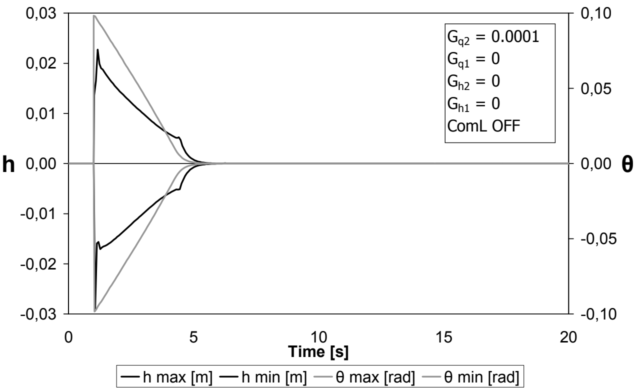


Figure 3 Fully operational system.

Figure 4 shows the dynamic behaviour of the system in the servovalve feedback spring failure condition. The failure occurs at time t = 2 s. With respect to Figure 3, the behaviour is substantially identical as long as the amplitude of the servomechanism input command is so large to produce end of travel displacements of the servovalve spool, because in this condition the feedback spring is practically ineffective. Some small differences are detectable when the amplitude of the input command is substantially reduced and the ends of travel are no longer important in the displacement of the servovalve mechanical elements. However the servomechanism, though affected by a limit cycle giving rise to fatigue damage, is able to perform a response on average close to the commanded position. In fact the limit cycle frequency is higher than any structural frequency, so its effect is marginal for the aeroelastic phenomenon.

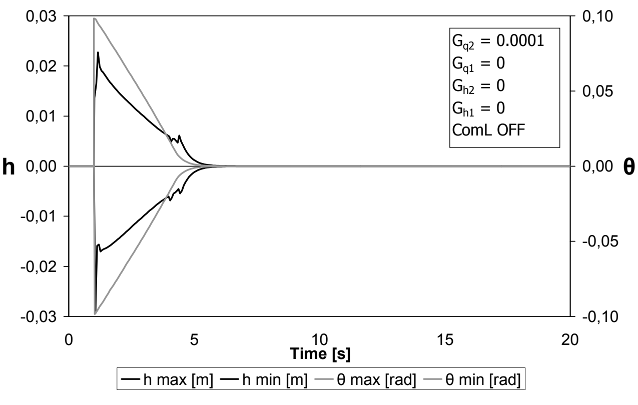


Figure 4 Feedback spring failure.

Figure 5 shows the dynamic behaviour of the system in case of hydraulic system pressure drop to a very low value (1 MPa) occurred at time t = 2 s, when both the servovalve spool and the moving surface are far from the centered position. The available actuation speed at a very low pressure value is very small, so the moving surface should no longer be able to retract to the null position. In this case the surface is progressively driven, through a series of oscillations, to the null position mainly by the aerodynamic load, overcoming the supply pressure effect. However the reduced available actuation rate prevents an effective flutter corrective action.

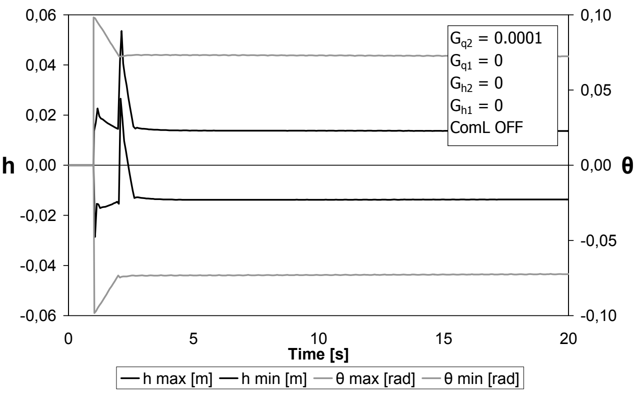


Figure 5 Hydraulic pressure drop to a very low value.

Figure 6 shows the dynamic behaviour of the system in case of hydraulic system pressure drop to a higher value than the previous case (5 MPa) occurred at time t = 2 s. The available actuation rate is higher than in Figure 5, so the flutter corrective action is slightly more effective.

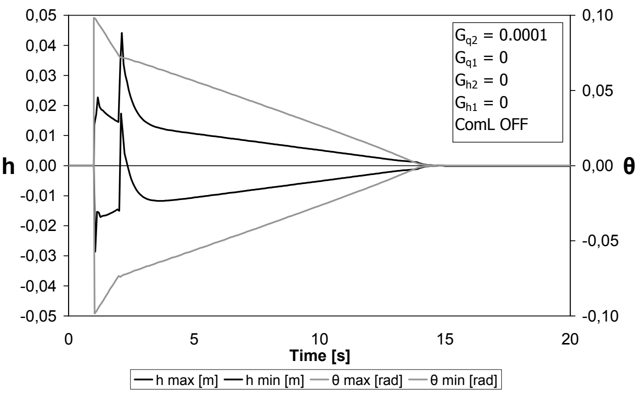


Figure 6 Hydraulic pressure drop to a higher value than the previous case.

Figure 7 shows the same pressure drop of Figure 5 at time t = 2 s, then followed by a pressure restore to the normal value (20 MPa) at time t = 5 s. As expected, it can be noted, till to 5 s, the same behaviour reported in Figure 5. At the pressure restore the corrective ability of the servomechanism is now fully available, and the behaviour of the system is similar to Figure 3.

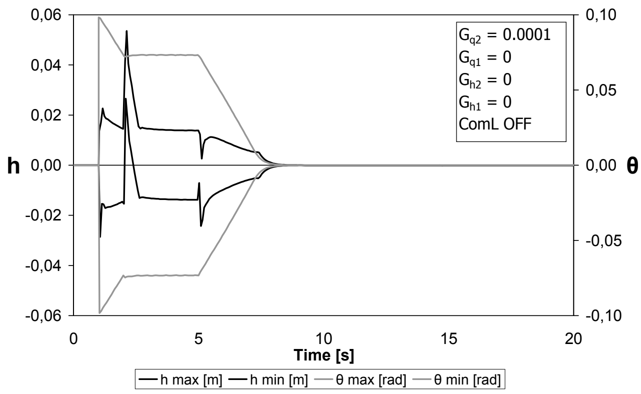


Figure 7 Hydraulic pressure drop and subsequent restore.

Figure 8 shows the dynamic behaviour of the system in case of whole active flutter control failure, intended as the loss of the servomechanism input command (constantly null), without any failure strictly regarding the servomechanism integrity. When the failure occurs, the surface is quickly retracted to the null position, remaining ineffective through the following part of the simulation. As expected, the flutter phenomenon is slightly divergent, as in case of absence of active flutter control.

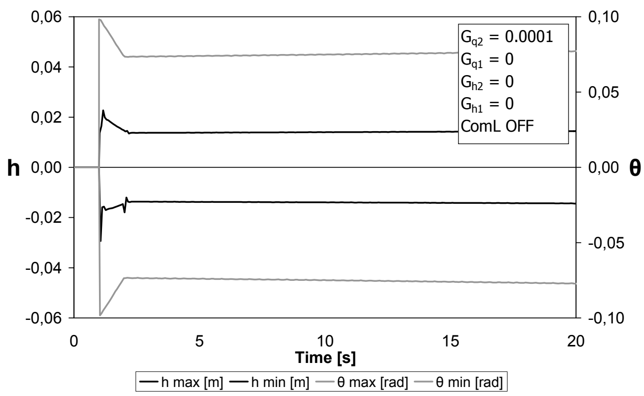


Figure 8 Whole active flutter control failure.

Figure 9 shows the dynamic behaviour of the system in case of incipient piston seizure, modelled as a marked rise of the friction force to a value slightly lower then the stall piston one. As a consequence, the servocontrol actuation rate, still possible, is however lower than usual, so the corrective capability is reduced.

Figure 10 shows the dynamic behaviour of the system in case of piston seizure, modelled as a more marked rise of the friction force to a value higher then the stall piston one. When the failure occurs, the surface is stopped in a position far from the centered one, and its flutter corrective action is lost. More, the not null surface position is able to keep the wing structure in a deformed position, as it is evident mainly in terms of vertical displacement.

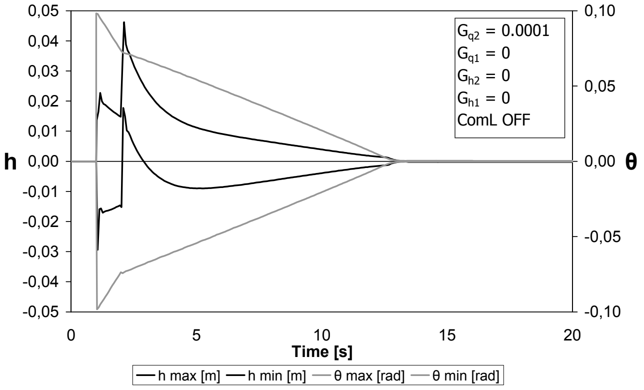


Figure 9 Incipient piston seizure.

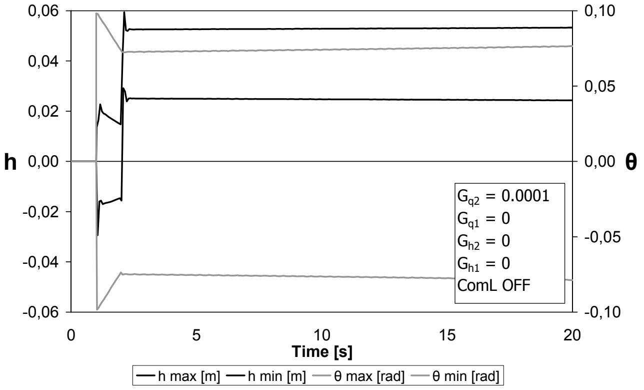


Figure 10 Piston seizure.

Figure 11 shows the dynamic behaviour of the system in case of marginal piston internal sealing failure, modelled as a medium growth of its leakage coefficient. Under low to medium aerodynamic loads, the actuation capability is slightly reduced (lower rate) but substantially preserved. As a consequence the flutter corrective action is slightly lower than the case shown in Fig. 3.

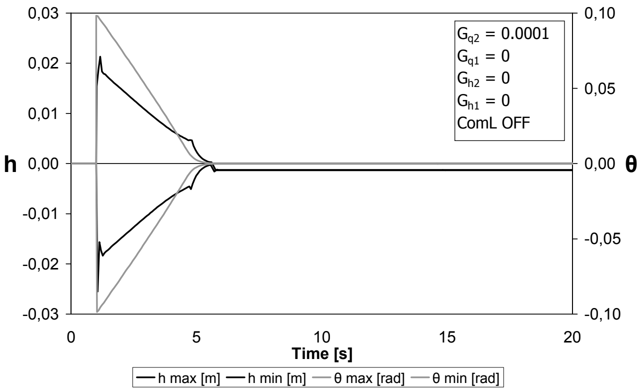


Figure 11 Marginal piston internal sealing failure.

Figure 12 shows the dynamic behaviour of the system in case of piston internal sealing failure, modelled as a large increase of its leakage coefficient. In this case the actuation capability is markedly reduced even under low aerodynamic loads. On the contrary the aerodynamic load is often able to overcome the input command and the surface deployment is mainly the consequence of the load itself. This effect produces a negative corrective action, so developing higher divergence rate.

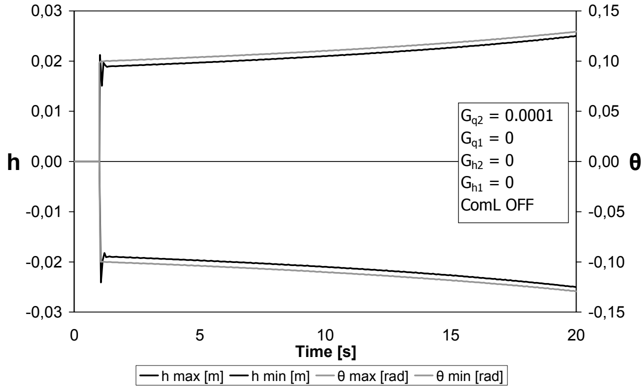


Figure 12 Piston internal sealing failure.

4 CONCLUSIONS

The results presented in this work are obtained in case of not redundant servosystem; so the failure effects are not limited by the action of the operative portion of an eventually redundant device. However the results are significant mainly for their conceptual aspects and show the possible criticality of a singular failure in a not redundant device. It can be noted that the more critical failures are those concerning the loss of the piston internal sealing, the total supply pressure drop or the total piston seizure. Sealing damage and pressure drop can be efficiently overcome by a proper redundancy; on the contrary, the piston seizure, particularly in case of force summed redundancies, must be considered seriously critical because the operative portion of the system may be incapable of overcoming the failure effects.

REFERENCES

[1] Borello L., Villero G. and Dalla Vedova M., 2008. Effects of nonlinearities and control law selection on active flutter suppression. *International Journal of Mechanics and Control,* Vol. 9, No. 1, pp. 27-39.

ISSN 1590-8844
International Journal of Mechanics and Control, Vol. 11, No. 02, 2010

TEMPLATE FOR PREPARING PAPERS FOR PUBLISHING IN INTERNATIONAL JOURNAL OF MECHANICS AND CONTROL

Author1*   Author2**

*   affiliation Author1

**   affiliation Author2

ABSTRACT

This is a brief guide to prepare papers in a better style for publishing in International Journal of Mechanics and Control (JoMaC). It gives details of the preferred style in a template format to ease paper presentation. The abstract must be able to indicate the principal authors' contribution to the argument containing the chosen method and the obtained results. (max 200 words)

Keywords: keywords list (max 5 words)

1 TITLE OF SECTION (E.G. INTRODUCTION)

This sample article is to show you how to prepare papers in a standard style for publishing in International Journal of Mechanics and Control.
It offers you a template for paper layout, and describes points you should notice before you submit your papers.

2 PREPARATION OF PAPERS

2.1 SUBMISSION OF PAPERS

The papers should be submitted in the form of an electronic document, either in Microsoft Word format (Word'97 version or earlier).
In addition to the electronic version a hardcopy of the complete paper including diagrams with annotations must be supplied. The final format of the papers will be A4 page size with a two column layout. The text will be Times New Roman font size 10.

Contact author: author1[1], author2[2]

[1]Address of author1.

[2]Address of author2 if different from author1's address.

2.2 DETAILS OF PAPER LAYOUT

2.2.1 Style of Writing

The language is English and with UK/European spelling. The papers should be written in the third person. Related work conducted elsewhere may be criticised but not the individuals conducting the work. The paper should be comprehensible both to specialists in the appropriate field and to those with a general understanding of the subject.
Company names or advertising, direct or indirect, is not permitted and product names will only be included at the discretion of the editor. Abbreviations should be spelt out in full the first time they appear and their abbreviated form included in brackets immediately after. Words used in a special context should appear in inverted single quotation mark the first time they appear. Papers are accepted also on the basis that they may be edited for style and language.

2.2.2 Paper length

Paper length is free, but should normally not exceed 10000 words and twenty illustrations.

2.2.3 Diagrams and figures

Figures and Tables will either be entered in one column or two columns and should be 80 mm or 160 mm wide respectively. A minimum line width of 1 point is required at actual size. Captions and annotations should be in 10 point with the first letter only capitalised *at actual size* (see Figure 1 and Table VII).

ISSN 1590-8844
International Journal of Mechanics and Control, Vol. 11, No. 02, 2010

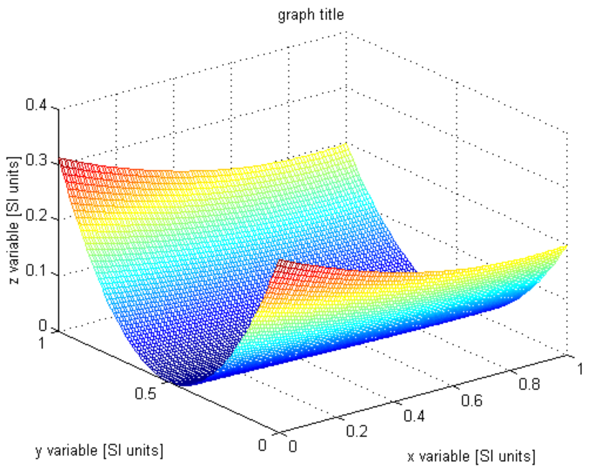


Figure 1 Simple chart.

Table VII - Experimental values

Robot Arm Velocity (rad/s)	Motor Torque (Nm)
0.123	10.123
1.456	20.234
2.789	30.345
3.012	40.456

2.2.4 Photographs and illustrations
Authors could wish to publish in full colour photographs and illustrations. Photographs and illustrations should be included in the electronic document and a copy of their original sent. Illustrations in full colour …

2.2.5 Equations
Each equation should occur on a new line with uniform spacing from adjacent text as indicated in this template. The equations, where they are referred to in the text, should be numbered sequentially and their identifier enclosed in parenthesis, right justified. The symbols, where referred to in the text, should be italicised.

- point 1
  - point 2
    - point 3

1. numbered point 1
   2. numbered point 2
      3. numbered point 3

$$W(d) = G(A_0, \sigma, d) = \frac{1}{T}\int_0^{+\infty} A_0 \cdot e^{-\frac{d^2}{2\sigma^2}} dt \quad (1)$$

3 COPYRIGHT

Authors will be asked to sign a copyright transfer form prior to JoMaC publishing of their paper. Reproduction of any part of the publication is not allowed elsewhere without permission from JoMaC whose prior publication must be cited. The understanding is that they have been neither previously published nor submitted concurrently to any other publisher.

4 PEER REVIEW

Papers for publication in JoMaC will first undergo review by anonymous, impartial specialists in the appropriate field. Based on the comments of the referees the Editor will decide on acceptance, revision or rejection. The authors will be provided with copies of the reviewers' remarks to aid in revision and improvement where appropriate.

5 REFERENCES (DESCRIPTION)

The papers in the reference list must be cited in the text. In the text the citation should appear in square brackets [ ], as in, for example, "the red fox has been shown to jump the black cat [3] but not when...". In the Reference list the font should be Times New Roman with 10 point size. Author's first names should be terminated by a 'full stop'. The reference number should be enclosed in brackets.
The book titles should be in *italics*, followed by a 'full stop'. Proceedings or journal titles should be in *italics.* For instance:

REFERENCES (EXAMPLE)

[1] Smith J., Jones A.B. and Brown J., *The title of the book*. 1st edition, Publisher, 2001.
[2] Smith J., Jones A.B. and Brown J., The title of the paper. *Proc. of Conference Name*, where it took place, Vol. 1, paper number, pp. 1-11, 2001.
[3] Smith J., Jones A.B. and Brown J., The title of the paper. *Journal Name*, Vol. 1, No. 1, pp. 1-11, 2001.
[4] Smith J., Jones A.B. and Brown J., *Patent title*, U.S. Patent number, 2001.

International Journal of Mechanics and Control – JoMaC
Published by Levrotto&Bella
TRANSFER OF COPYRIGHT AGREEMENT

NOTE: Authors/copyright holders are asked to complete this form signing section A, B or C and mail it to the editor office with the manuscript or as soon afterwards as possible.	*Editor's office address:* Andrea Manuello Bertetto Elvio Bonisoli *Dept. of Mechanics* *Technical University – Politecnico di Torino* *C.so Duca degli Abruzzi, 24 – 10129 Torino – Italy* *e_mail: jomac@polito.it* *fax n.: +39.011.564.6999*

The article title:

By:____

To be Published in ***International Journal of Mechanics and Control JoMaC***
Official legal Turin court registration Number 5320 (5 May 2000) - reg. Tribunale di Torino N. 5390 del 5 maggio 2000

A Copyright to the above article is hereby transferred to the JoMaC, effective upon acceptance for publication. However the following rights are reserved by the author(s)/copyright holder(s):
1. All proprietary rights other than copyright, such as patent rights;
2. The right to use, free or charge, all or part of this article in future works of their own, such as books and lectures;
3. The right to reproduce the article for their own purposes provided the copies are not offered for sale.
To be signed below by all authors or, if signed by only one author on behalf of all co-authors, the statement A2 below must be signed.

A1. All authors:

SIGNATURE____DATE_______________ SIGNATURE____DATE_______________

PRINTED NAME____ PRINTED NAME____

SIGNATURE____DATE_______________ SIGNATURE____DATE_______________

PRINTED NAME____ PRINTED NAME____

A2. One author on behalf of all co-authors:
"I represent and warrant that I am authorised to execute this transfer of copyright on behalf of all the authors of the article referred to above"

PRINTED NAME____

SIGNATURE____ TITLE____ DATE______________________

B. The above article was written as part of duties as an employee or otherwise as a work made for hire. As an authorised representative of the employer or other proprietor. I hereby transfer copyright to the above article to Editel-Pozzo Gros Monti effective upon publication. However, the following rights are reserved:
1. All proprietary rights other than copyright, such as patent rights;
2. The right to use, free or charge, all or part of this article in future works of their own, such as books and lectures;
3. The right to reproduce the article for their own purposes provided the copies are not offered for sale.

PRINTED NAME____

SIGNATURE____ TITLE____ DATE______________________

C. I certify that the above article has been written in the course of employment by the United States Government so that no copyright exists, or by the United Kingdom Government (Crown Copyright), thus there is no transfer of copyright.

PRINTED NAME____

SIGNATURE____ TITLE____ DATE______________________

CONTENTS

next number scheduled titles:

Dynamic And Energy Analysis of a Production System of Filament Wound Elbows
G. Dionoro, P. Buonadonna and A. Tronci

Design and Simulation of Cassino Hexapode Walking Machine
G. Carbone, M. Suciu, M. Ceccarelli and D. Pisla

Robot Assisted Laser Scanning
C. Rossi, S. Savino and S. Strano

Evaluation of Feasibility of Mechanical Harvesting of Myrtle Berries (Myrtus Communis L.)
F. Gambella and F. Paschino

Nonlinear Elastic Characteristic of Magnetic Suspensions through Hilbert Transform
E. Bonisoli